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(54) **SYSTEM AND METHOD FOR MONITORING
PIEZOELECTRIC MATERIAL
PERFORMANCE**

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(57) **ABSTRACT**

A system and method are provided for monitoring performance capacity of a piezoelectric material that may form part of an actuator or sensor device. A switch is used to selectively electrically couple an inductor to the piezoelectric material to form an inductor-capacitor circuit. Resonance is induced in the inductor-capacitor circuit when the switch is operated to create the circuit. The resonance of the inductor-capacitor circuit is monitored with the frequency of the resonance being indicative of performance capacity of the device's piezoelectric material.

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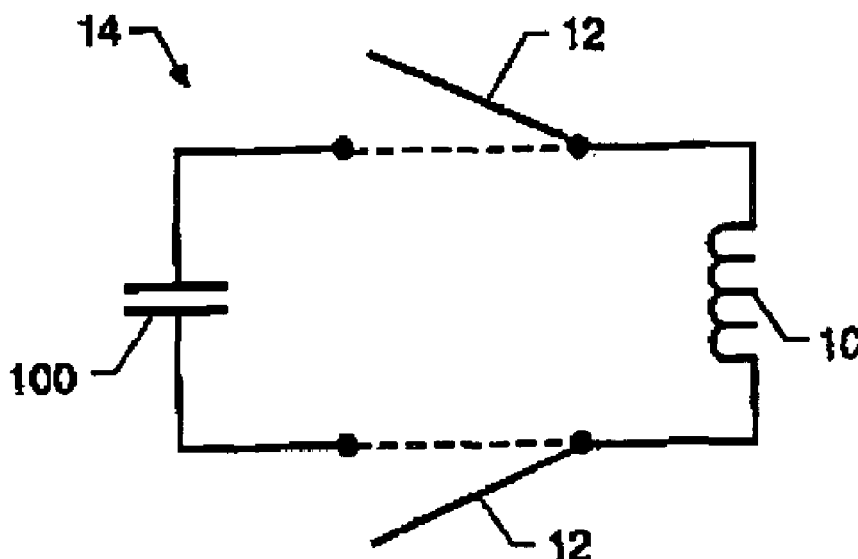
(51) **Int. Cl.**
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(52) **U.S. Cl.** **310/316.01; 310/319**

(58) **Field of Classification Search** **310/316.01, 310/317, 319, 311**

See application file for complete search history.

33 Claims, 3 Drawing Sheets



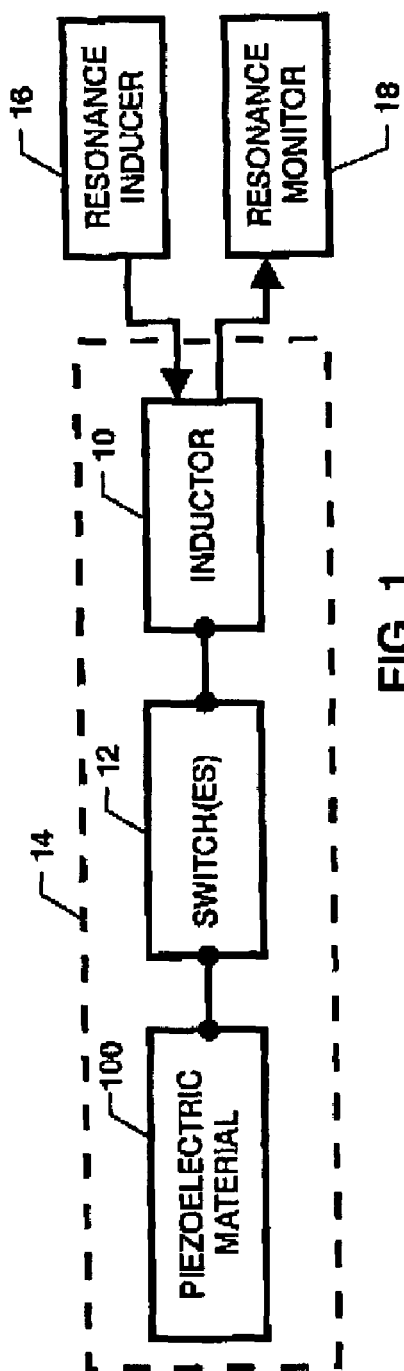


FIG. 1

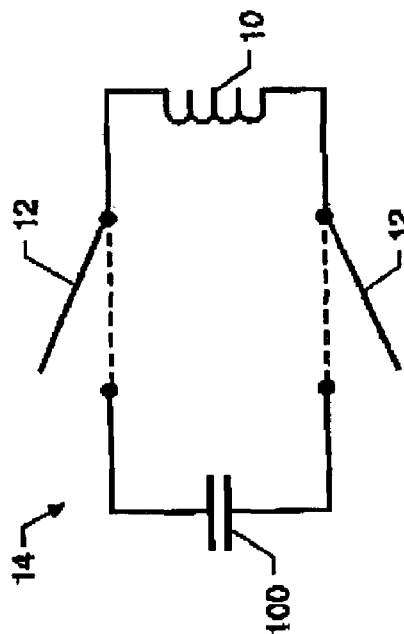


FIG. 2

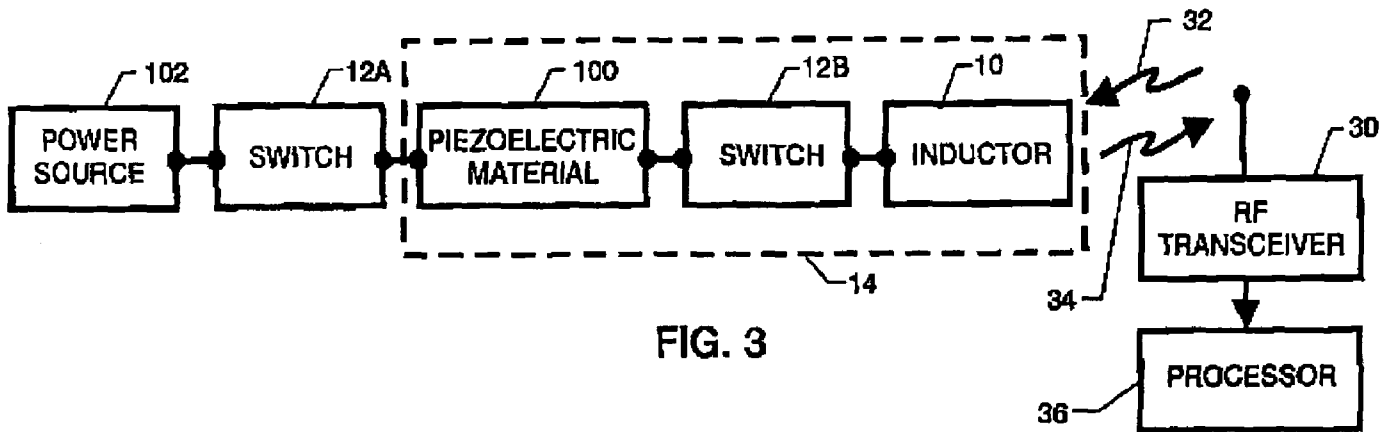


FIG. 3

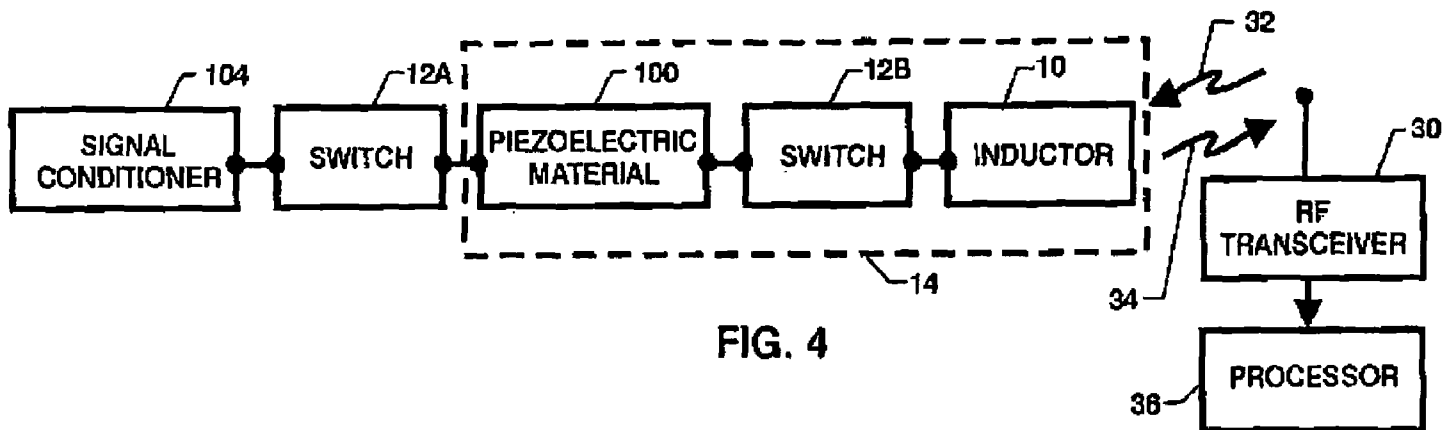


FIG. 4

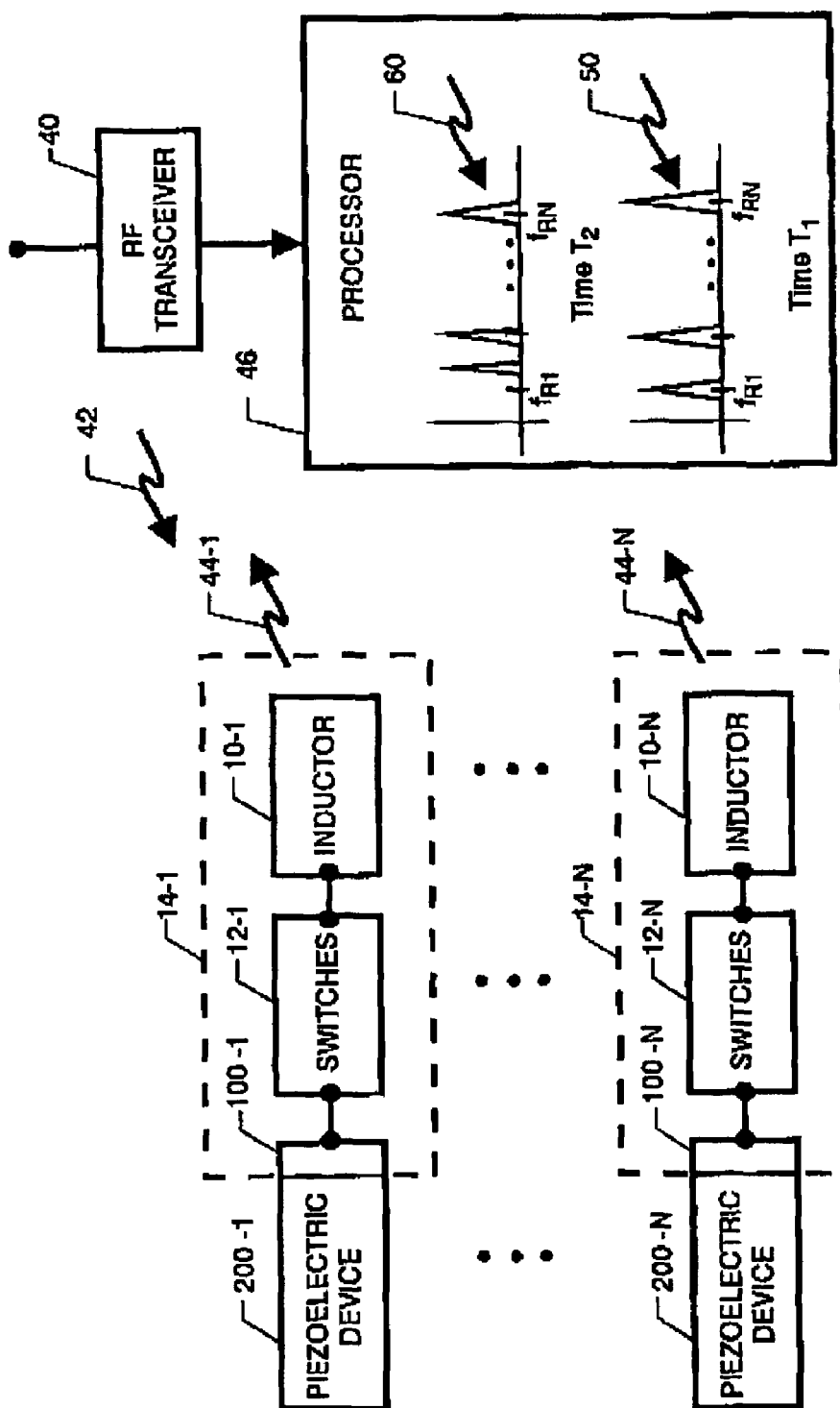


FIG. 5

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SYSTEM AND METHOD FOR MONITORING PIEZOELECTRIC MATERIAL PERFORMANCE

ORIGIN OF THE INVENTION

The invention described herein was made by employees of the United States Government and may be manufactured and used by or for the Government for governmental purposes without the payment of any royalties thereon or therefor.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to piezoelectric material performance. More specifically, the invention is a system and method for monitoring piezoelectric material, such as the type used in actuators and sensors, in order to evaluate the piezoelectric material's performance capacity.

2. Description of the Related Art

Piezoelectric material-based sensors and actuators are used extensively in aircraft, spacecraft, and in a wide variety of other electromechanical applications to include automotive noise control, automotive airbag sensing circuitry, and traffic control sensing circuitry, just to name a few. In general, these are small actuators/sensors that are easily embedded in structures. Unfortunately, once embedded in structures, it is difficult to quickly and quantitatively ascertain the performance capacity of the actuator/sensor devices which may deteriorate over time due to changes in the piezoelectric material.

SUMMARY OF THE INVENTION

Accordingly, it is an object of the present invention to provide a method and system for monitoring the performance capacity of piezoelectric materials that may be used in various actuator and/or sensor applications.

Other objects and advantages of the present invention will become more obvious hereinafter in the specification and drawings.

In accordance with the present invention, a system and method are provided for monitoring performance capacity of a piezoelectric material. A switch is used to selectively electrically couple an inductor to the piezoelectric material, whereby an inductor-capacitor circuit is formed with the piezoelectric material forming the capacitor in the inductor-capacitor circuit. The switch can also be operated to electrically decouple the inductor from the piezoelectric material. Resonance is induced in the inductor-capacitor circuit when the switch is operated to create the circuit. The resonance of the inductor-capacitor circuit is monitored with the frequency of the resonance being indicative of performance capacity of the piezoelectric material. The system and method can be used in conjunction with piezoelectric actuator and/or sensor devices in order to evaluate the performance capacity of the devices.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a system for monitoring the performance capacity of a piezoelectric material in accordance with the present invention;

FIG. 2 is a circuit schematic of the inductor-capacitor circuit formed for the monitoring process of the present invention;

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FIG. 3 is a schematic view of a piezoelectric actuator device coupled to the system that monitors the performance capacity of the device in accordance with the present invention;

FIG. 4 is a schematic view of a piezoelectric sensor device coupled to the system that monitors the performance capacity of the device in accordance with the present invention; and

FIG. 5 is a block diagram illustrating the system and method of the present invention for simultaneously monitoring the performance capacity of a plurality of piezoelectric devices in accordance with the present invention.

DETAILED DESCRIPTION OF THE INVENTION

Referring now to the drawings, and more particularly to FIG. 1, a block diagram illustrates the basic elements comprising a system for monitoring the performance of a piezoelectric material **100** in accordance with the present invention. For many applications, as will be explained further below, piezoelectric material **100** will be an element of a device (e.g., an actuator or sensor) in which the piezoelectric material forms the device's electromechanical work producing or sensing component. In these applications, the performance capacity of piezoelectric material **100** serves as an indicator of the performance capacity of the device itself. However, the present invention can also be used to monitor performance capacity of piezoelectric material **100** in isolation as illustrated in FIG. 1.

An inductor **10** is selectively coupled to piezoelectric material **100** by one or more switch(es) **12** such that an inductor-capacitor circuit **14** (e.g., a serial or parallel circuit) includes inductor **10** and piezoelectric material **100**, where piezoelectric material **100** forms the capacitor portion of circuit **14**. Inductor **10** should be stable in terms of its inductance value when piezoelectric material **100** forms the capacitor portion of circuit **14**. Accordingly, inductor **10** is typically a simple coil or spiral of wire with the wire size and number of coils/spirals being selected such that the resulting inductor-capacitor circuit **14** will be tuned to a selected resonant frequency f_R . The circuit schematic equivalent of inductor-capacitor circuit **14** is shown in FIG. 2 where the dashed line coupling (i.e., switch(es) **12** are closed) of inductor **10** to piezoelectric material **100** depict a monitoring state of the present invention. The solid line coupling (i.e., switch(es) **12** are open) of inductor **10** from piezoelectric material **100** depict a non-monitoring state. The type and number of switches **12** used to create the open and closed circuit is not a limitation of the present invention. For example, switches **12** could be manually or remotely controlled, could be closed/opened by the insertion/removal of an electrical plug, controlled in a wireless fashion, etc., without departing from the scope of the present invention.

With inductor-capacitor circuit **14** in the monitoring state, a resonance inducer **16** provides energy to inductor-capacitor circuit **14** to cause circuit **14** to resonate and generate energy at a frequency to be monitored or f_M , where f_M is a function of the current inductance and current capacitance of circuit **14**. Since inductor **10** was chosen to have a stable inductance value, monitored frequency f_M changes with changes in the capacitance of piezoelectric material **100**. Large changes in capacitance of piezoelectric material **100** will result when piezoelectric material **100** undergoes degradation, e.g., mechanical degradation such as cracks or breaks, fatigue due to excessive mechanically-induced or electrically-induced stresses that build up over time or are

caused by sudden mechanical or electrical overloads, etc. Thus, the present invention monitors the performance capacity of piezoelectric material **100** by continually or occasionally inducing/monitoring frequency f_M and comparing same to the originally tuned resonant frequency f_R . Differences between f_R and f_M will be significant when the performance capacity of piezoelectric material **100** has changed. Note that if the monitored frequency f_M is different or shifted with respect to the original resonant frequency f_R but it is determined that the shift is not indicative of performance degradation, the monitored frequency f_M could be used to establish a new baseline resonant frequency f_R . For example, the present invention could be used to track changes in resonant frequency prior to and after electrical poling of piezoelectric material **100**. As is known in the art, such electrical poling typically occurs during the preparation of a piezoelectric material for use in a sensor or actuator device.

The energy provided by resonance inducer **16** can be directly (i.e., via hardware connection) or indirectly coupled to inductor-capacitor circuit **14**. In terms of an indirect coupling of such resonance-inducing energy, resonance inducer **16** can be a radio frequency (RF) generator that transmits RF energy from a location that may be remote from circuit **14** where the RF energy includes resonant frequency f_R of circuit **14**. A resonance monitor **18** can similarly be directly or indirectly coupled to inductor-capacitor circuit **14** in order to sense/detect monitored frequency f_M . The energy associated with monitored frequency f_M is essentially RF energy that can be sensed/detected in a remote wireless fashion. Accordingly, resonance monitor **18** can be an RF receiver tuned to be sensitive to a band that includes resonant frequency f_R and possible values of monitored frequency f_M .

As mentioned above, piezoelectric material **100** is frequently incorporated in an actuator or sensor device. The present invention can be adapted to work with the devices in order to monitor the performance capacity thereof by monitoring the performance capacity of the device's piezoelectric material. Accordingly, FIG. 3 illustrates a piezoelectric actuator device and an embodiment of the monitoring system of the present invention, and FIG. 4 illustrates a piezoelectric sensing device and an embodiment of the monitoring system of the present invention.

Referring first to FIG. 3, the piezoelectric actuator device includes piezoelectric material **100** and a power source **102** that is electrically coupled to material **100**. To implement the present invention, switch **12A** is used to selectively couple/uncouple power source **102** to/from piezoelectric material **100**, while switch **12B** is used to couple/uncouple inductor **10** to/from piezoelectric material **100**. To monitor the frequency f_M of inductor-capacitor circuit **14** when switch **12A** is opened and switch **12B** is closed, an RF transceiver **30** transmits RF energy **32** thereby causing circuit **14** to resonate and generate RF energy **34** at the monitored frequency f_M which, in turn, is sensed by RF transceiver **30**. The transmit and receive portions of transceiver **30** can be co-located or maintained at distinct locations without departing from the scope of the present invention.

The monitored frequency f_M can be compared with the original tuned resonant frequency f_R to determine if there are appreciable changes between f_R and f_M indicative of a change in the performance capacity of the piezoelectric actuator. The comparison between f_R and f_M can occur, for example, at a processor **36** coupled to RF transceiver **30**. The original tuned resonant frequency f_R can be determined/measured to form the baseline that will be compared with one or more monitored frequencies f_M that are collected over

a period of time. The original tuned resonant frequency f_R can be stored or archived by processor **36** for comparison with the monitored frequencies f_M . The times for collecting monitored frequency f_M can occur at regularly or irregularly scheduled intervals.

In operation, assuming the piezoelectric device is in its operational state (i.e., switch **12A** is closed and switch **12B** is open), the monitoring state of the present invention is implemented as follows. Inductor **10** is electrically coupled to piezoelectric material **100** by closing switch **12B**. As mentioned above, the closing/opening of switch **12B** can be controlled in a variety of manual, remote, hardwired or wireless fashions without departing from the scope of the present invention. With switch **12B** closed, RF transceiver **30** transmits RF energy **32** in order to induce resonance in circuit **14** which results in generation of RF energy **34**. Prior to monitoring frequency f_M of RF energy **34**, switch **12A** is opened so that the current will flow through both the low-resistance inductor **10** and the high-resistance piezoelectric material **100**, a situation that would not occur if power source **102** were still coupled to piezoelectric material **100** when trying to monitor f_M . The opening of switch **12A** can be tied to the closing of switch **12B** in a "smart" fashion. That is, switch **12A** could be configured to sense the closing of switch **12B** and then open so that the monitoring process can begin.

Referring now to FIG. 4, the piezoelectric sensor device includes piezoelectric material **100** and a signal conditioner **104** (e.g., a charge amplifier that resolves the current and/or voltage generated by the piezoelectric material into measurements of current, voltage, and/or other engineering metrics) that is electrically coupled to material **100**. Monitoring the performance capacity of piezoelectric material **100** is achieved in the same fashion as described above for the piezoelectric actuator device and, therefore, need not be described further.

The present invention can be used to simultaneously monitor a plurality of piezoelectric devices as will now be described with the aid of FIG. 5. Each of a plurality of piezoelectric devices **200-1**, . . . , **200-N** have an inductor **10-1**, . . . , **10-N** coupled to the devices' piezoelectric material **100-1**, . . . , **100-N** via a switch **12-1**, . . . , **12-N** that, when closed, form inductor-capacitor circuits **14-1**, . . . , **14-N**. For clarity of illustration, the power source or signal conditioner associated with each of devices **200-1**, . . . , **200-N**, and the switches used to couple/uncouple the power source or signal conditioner from its corresponding material, have been omitted.

Inductors **10-1**, . . . , **10-N** are selected such that each inductor-capacitor circuit **14-1**, . . . , **14-N** has a unique original tuned resonant frequency f_{R1} , . . . , f_{RN} . An RF transceiver **40** is configured to generate RF energy **42** over a transmission band of frequencies to include all of f_{R1} , . . . , f_{RN} . The transmitted RF energy **42** excites each inductor-capacitor circuit **14-1**, . . . , **14-N** to resonance whereby corresponding RF energies **44-1**, . . . , **44-N** are generated. RF transceiver **40** is further configured to be sensitive to RF energies **44-1**, . . . , **44-N** in a reception band that includes the transmission band. A processor **46** coupled to RF transceiver **40** archives the set of original tuned resonant frequencies f_{R1} , . . . , f_{RN} and compares them to the monitored frequencies f_{M1} , . . . , f_{MN} associated with RF energies **44-1**, . . . , **44-N**. For example, processor **46** could be used to generate a spectral map **50** at a baseline time T_1 to identify all of the original tuned resonant frequencies f_{R1} , . . . , f_{RN} . Then, at a monitoring time T_2 , processor **46** could be used to generate a spectral map **60** to identify all of

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the monitored frequencies f_{M1}, \dots, f_{MN} . Processor 46 could further be used to subtract spectral map 60 from spectral map 50. If there have been no capacitive changes in any of piezoelectric materials 100-1, \dots , 100-N from time T_1 to time T_2 , the difference between two spectral maps each of f_{R1}, \dots, f_{RN} will be zero. However, if a spectral “spike” is present at one or more of f_{R1}, \dots, f_{RN} , the associated i-th piezoelectric device may have experienced performance degradation since its monitored frequency f_{Mi} is different from its original tuned resonant frequency f_{Ri} .

The advantages of the present invention are numerous. Performance capacity of piezoelectric materials and their devices can be diagnosed quickly and efficiently. The various switches and inductors can be partially or fully integrated with the piezoelectric device or can be included in self-contained monitoring system that is coupled to a piezoelectric device where needed. Monitoring can be accomplished using RF interrogation thereby eliminating the need to physically access the devices in order to evaluate them.

Although the invention has been described relative to a specific embodiment thereof, there are numerous variations and modifications that will be readily apparent to those skilled in the art in light of the above teachings. It is therefore to be understood that, within the scope of the appended claims, the invention may be practiced other than as specifically described.

What is claimed as new and desired to be secured by Letters Patent of the United States is:

1. A system for monitoring performance capacity of a piezoelectric material, comprising:

a piezoelectric material;

an inductor;

switch means coupled to said inductor and operable to selectively (i) electrically couple said inductor to said piezoelectric material wherein an inductor-capacitor circuit is formed with said piezoelectric material forming a capacitor in said inductor-capacitor circuit, and (ii) electrically decouple said inductor from said piezoelectric material;

means for inducing resonance in said inductor-capacitor circuit; and

means for monitoring said resonance wherein a frequency of said resonance is indicative of performance capacity of said piezoelectric material.

2. A system as in claim 1 wherein said piezoelectric material is adapted to be coupled to a power source, and wherein said system further comprises second switch means adapted to be coupled between said power source and said piezoelectric material, said second switch means operable to (i) electrically decouple said power source from said piezoelectric material prior to a time when said resonance is to be monitored, and (ii) electrically couple said power source to said piezoelectric material after said resonance has been monitored.

3. A system as in claim 1 wherein said piezoelectric material is adapted to be coupled to a signal conditioner, and wherein said system further comprises second switch means adapted to be coupled between said signal conditioner and said piezoelectric material, said second switch means operable to (i) electrically decouple said signal conditioner from said piezoelectric material prior to a time when said resonance is to be monitored, and (ii) electrically couple said signal conditioner to said piezoelectric material after said resonance has been monitored.

4. A system as in claim 1 wherein said inductor comprises a spiraled wire.

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5. A system as in claim 1 wherein said switch means is remotely controllable.

6. A system as in claim 2 wherein said switch means and said second switch means are remotely controllable.

7. A system as in claim 3 wherein said switch means and said second switch means are remotely controllable.

8. A system as in claim 1 wherein said means for inducing comprises a radio frequency generator.

9. A system as in claim 1 wherein said means for monitoring comprises a radio frequency receiver.

10. A system as in claim 1 wherein said means for inducing and said means for monitoring comprise a radio frequency (RF) transceiver for generating RF energy to induce said resonance and for receiving RF energy resulting from said resonance.

11. A system as in claim 1 wherein said means for monitoring comprises:

means for archiving a plurality of measurements of said frequency taken over a period of time; and

means for comparing said plurality of measurements to monitor changes in said frequency associated therewith.

12. A method of monitoring performance capacity of a piezoelectric material, comprising the steps of:

coupling an inductor to a piezoelectric material wherein an inductor-capacitor circuit is formed with said piezoelectric material forming a capacitor in said inductor-capacitor circuit;

inducing resonance in said inductor-capacitor circuit;

monitoring a frequency of said resonance;

decoupling said inductor from said piezoelectric material; and

repeating said steps of coupling, inducing, monitoring and decoupling wherein changes in said frequency are indicative of changes in performance capacity of said piezoelectric material.

13. A method of monitoring performance capacity of a piezoelectric material, comprising the steps of:

coupling an inductor to a piezoelectric material wherein an inductor-capacitor circuit is formed with said piezoelectric material forming a capacitor in said inductor-capacitor circuit;

inducing resonance in said inductor-capacitor circuit;

monitoring a frequency of said resonance;

decoupling said inductor from said piezoelectric material; and

repeating said steps of coupling, inducing, monitoring and decoupling wherein changes in said frequency are indicative of changes in performance capacity of said piezoelectric material;

wherein said piezoelectric material has a power source coupled thereto, and wherein said method further comprises the step of decoupling said power source from said piezoelectric material prior to said step of monitoring.

14. A method of monitoring performance capacity of a piezoelectric material, comprising the steps of:

coupling an inductor to a piezoelectric material wherein an inductor-capacitor circuit is formed with said piezoelectric material forming a capacitor in said inductor-capacitor circuit;

inducing resonance in said inductor-capacitor circuit;

monitoring a frequency of said resonance;

decoupling said inductor from said piezoelectric material; and

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repeating said steps of coupling, inducing, monitoring and decoupling wherein changes in said frequency are indicative of changes in performance capacity of said piezoelectric material;

wherein said piezoelectric material has a signal conditioner coupled thereto, and wherein said method further comprises the step of decoupling said signal conditioner from said piezoelectric material prior to said step of monitoring.

15. A method according to claim 12 wherein said step of inducing comprises the step of transmitting radio frequency (RF) energy from a first location that is remote with respect to said inductor-capacitor circuit.

16. A method according to claim 15 wherein said step of monitoring comprises the step of receiving RF energy resulting from said resonance at a second location that is remote with respect to said inductor-capacitor circuit.

17. A method according to claim 16 wherein said first location and said second location are co-located with one another.

18. A method according to claim 12 wherein said step of repeating occurs at regular intervals.

19. A method according to claim 12 wherein said step of repeating occurs at irregular intervals.

20. A system for monitoring performance capacity of a device that includes one of a power source and a signal conditioner coupled to a piezoelectric material, comprising:

an inductor;

first switch means coupled to said inductor and adapted to be coupled to said piezoelectric material, said first switch means operable to selectively (i) electrically couple said inductor to said piezoelectric material wherein an inductor-capacitor circuit is formed with said piezoelectric material forming a capacitor in said inductor-capacitor circuit, and (ii) electrically decouple said inductor from said piezoelectric material;

second switch means adapted to be coupled between said piezoelectric material and one of said power source and said signal conditioner, said second switch means operable to electrically couple and decouple said piezoelectric material from said one of said power source and said signal conditioner;

means for inducing resonance in said inductor-capacitor circuit; and

means for monitoring said resonance when said second switch means is operated to decouple said piezoelectric material from said one of said power source and said signal conditioner, wherein a frequency of said resonance is indicative of performance capacity of said device.

21. A system as in claim 20 wherein said means for inducing comprises a radio frequency generator.

22. A system as in claim 20 wherein said means for monitoring comprises a radio frequency receiver.

23. A system as in claim 20 wherein a plurality of said devices are to be monitored simultaneously with each of said devices having (i) one said inductor, (ii) one said first switch means, and (iii) one said second switch means associated therewith, such that a plurality of inductor-capacitor circuits are formed when each said first switch means electrically couples a corresponding one said inductor to a corresponding one said piezoelectric material, each said inductor having an inductance such that each of said plurality of inductor-capacitor circuits has a unique resonance frequency associated therewith that is indicative of an acceptable level of performance capacity of a corresponding one of said devices, wherein said means for inducing comprises a radio

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frequency (RF) generator for generating RF energy across a frequency band that encompasses each said unique resonance frequency of said plurality of inductor-capacitor circuits.

24. A system as in claim 23 wherein said means for monitoring comprises:

an RF receiver for receiving each said resonance at its corresponding frequency; and

means coupled to said RF receiver for generating a spectral map using each said resonance at first and second points in time, wherein changes between said spectral map associated with said first point in time and said spectral map associated with said second point in time at each said unique resonance frequency are indicative of changes in performance capacity of corresponding ones of said devices.

25. A system as in claim 20 wherein said inductor comprises a spiraled wire.

26. A system as in claim 20 wherein said first switch means and said second switch means are remotely controllable.

27. A system for monitoring performance capacity of a piezoelectric device having one of a power source and a signal conditioner coupled thereto, comprising:

a piezoelectric device that includes a piezoelectric material coupled to one of a power source and a signal conditioner;

an inductor;

first switch means coupled to said inductor and said piezoelectric material, said first switch means operable to selectively (i) electrically couple said inductor to said piezoelectric material wherein an inductor-capacitor circuit is formed with said piezoelectric material forming a capacitor in said inductor-capacitor circuit, and (ii) electrically decouple said inductor from said piezoelectric material;

second switch means coupled between said piezoelectric material and one of said power source and said signal conditioner, said second switch means operable to electrically couple and decouple said piezoelectric material from said one of said power source and said signal conditioner;

means for inducing resonance in said inductor-capacitor circuit; and

means for monitoring said resonance when said second switch means is operated to decouple said piezoelectric material from said one of said power source and said signal conditioner, wherein a frequency of said resonance is indicative of performance capacity of said device.

28. A system as in claim 27 wherein said means for inducing comprises a radio frequency generator.

29. A system as in claim 27 wherein said means for monitoring comprises a radio frequency receiver.

30. A system as in claim 27 wherein a plurality of said devices are to be monitored simultaneously with each of said devices having a power source coupled to a piezoelectric material and with each of said devices having (i) one said inductor, (ii) one said first switch means, and (iii) one said second switch means associated therewith, such that a plurality of inductor-capacitor circuits are formed when each said first switch means electrically couples a corresponding one said inductor to a corresponding one said piezoelectric material, each said inductor having an inductance such that each of said plurality of inductor-capacitor circuits has a unique resonance frequency associated therewith that is indicative of an acceptable level of performance capacity of

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a corresponding one of said devices, wherein said means for inducing comprises a radio frequency (RF) generator for generating RF energy across a frequency band that encompasses each said unique resonance frequency of said plurality of inductor-capacitor circuits.

31. A system as in claim **30** wherein said means for monitoring comprises:

an RF receiver for receiving each said resonance at its corresponding frequency; and

means coupled to said RF receiver for generating a spectral map using each said resonance at first and second points in time, wherein changes between said

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spectral map associated with said first point in time and said spectral map associated with said second point in time at each said unique resonance frequency are indicative of changes in performance capacity of corresponding ones of said devices.

32. A system as in claim **27** wherein said inductor comprises a spiraled wire.

33. A system as in claim **27** wherein said first switch means and said second switch means are remotely controllable.

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